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AMORPHOUS SILICON SENSOR WITH MICRO-SPRING INTERCONNECTS FOR ACHIEVING HIGH UNIFORMITY IN INTEGRATED LIGHT-EMITTING SOURCES

Background of the Invention

Field of the Invention

This invention relates to imaging systems using a sensor element to control the emission of at least some of the light of one or more light-emitting sources. In particular, this invention is directed to architectures, characteristics and methods of integration of a light sensor configuration with different light sources, using micro-fabricated metal spring contacts.

Technical Background

Image printbars which are used in imaging systems are well known in the art. Such printbars are generally comprised of a linear array of a plurality of discreet, light-emitting sources. Examples of such printbars include light-emitting diodes and lasers. A method of forming lasers in semiconductor material, which may be used in the formation of laser printbars has been taught by, for example, U.S. Patent No. 5,978,408 to Thornton, entitled, “Highly Compact Vertical Cavity Surface Emitting Lasers”, issued November 2, 1999; and U.S. Patent No. 5,843,802 to Beernink, et al., entitled, “Semiconductor Laser Formed by Layer Intermixing”, issued December 1, 1998, both commonly assigned and hereby incorporated by reference.

In a typical printbar arrangement, a large number of individual light-emitting sources are arranged in an elongated, planer array that is placed adjacent an image recording member. By providing relative motion between the printbar and the image recording member, the printbar scans the image recording member, and by selectively illuminating the individual light-emitting sources, a desired light image is recorded on the image recording member.

The selective illumination of the individual light-emitting sources is performed according to image-defining data that is applied to printbar driver circuitry. Conventionally, the image-defining data takes the form of simple binary video data signals. Those data signals may be from any of a number of data sources such as a Raster Input Scanner (RIS), a computer, a word processor, or a facsimile machine. Typically, the binary video data is clocked into a shift register. After completely shifting the data into the shift register, the contents of the shift register is transferred in parallel into latch circuits for temporary storage. Then, upon the occurrence of a start of a line signal, the latch data is applied to the printbar drive circuit which thereby illuminates the individual light-emitting sources of the printbar so as to produce a line of the latent image. A complete latent image is formed by performing successive line exposures until the image is produced.

Due to their narrow beam profile and high efficiency, photolithographically configured laser printbars have been found to provide certain advantages. Proposed laser printbars consist of an array of Vertical-Cavity Surface-Emitting Lasers (VCSELs) which may be designed with as small as 3 μm pitch. At such a pitch, a 4cm-long laser chip would accommodate more than 13,300 individually addressable laser elements, more than necessary for 1,200dpi printing on a standard 11inch-long paper, where 13,200 elements are required. A drawback of such a large number or light sources, ultra-high density-packed, is the expectation of non-uniformity of laser responses. This non-uniformity has the potential for high spatial frequency that makes the effect on printed images noticeable to the human eye.

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One manner of addressing non-uniformity is to perform a calibration when the printbar is being manufactured. A problem with this process is that it does not address aging of the lasers, fluctuations in driver chip operation or environmental variations such as temperature and humidity, among others.

A second proposal is to form a sensor or detector as part of the printbar in order to perform periodic calibrations during the lifetime of the printbar. This concept is described in U.S. Patent Serial No. 08/921,942, entitled, Semiconductor Laser With Integrated Detector Structure, Thornton et al., filed August 27, 1997. A drawback with this proposal is the complexity of forming the device.

Similar issues may be present in many other imaging systems where one or more light-emitting sources need to be controlled in order to address issues like intrinsic non-uniformity, drift of characteristics or differential aging.

Therefore, it has been considered desirable to provide an apparatus and method to integrate a sensor element in a hybrid structure with a printbar or another compatible light-emitting source using simple patterned micro-spring metal contacts.

Summary of the Invention

Provided is a hybrid structure or device integrated in a substrate, where in some cases the substrate is substantially transparent to light at infrared wavelengths. Integrated on the substrate are a plurality of micro-spring interconnects, where the micro-spring interconnects are formed of an elastic material that is initially fixed to a surface on the substrate. Upon release of a sacrificial layer a free portion moves out of the plane of the substrate in a self-assembling. A sensor is formed on the same substrate, and includes an active layer and contacts. The active layer may be substantially transparent to light at infrared wavelengths. The micro-spring interconnects and the sensor are integrated on the substrate and configured using a compatible manufacturing process.

With attention to a further embodiment of the present invention, a light-emitting source is provided which may be an array of individual light-emitting sources. The light sources may be lasers such as, Vertical Cavity, Surface-Emitting Lasers (VCSELs), which are formed on the substrate, and the VCSELs are capable of emitting light at an infrared wavelength. Other light sources may also be used such as an array of light emitting diodes (LEDs). The substrate holding the spring contacts and sensor, and the substrate including the light sources are aligned such that at least a portion of the light emitted by the light source is directed through the second substrate and the sensor which may be, substantially transparent at infrared wavelengths.

Separate embodiments describe similar integration schemes for less directional light-sources, such as Light-Emitting Diodes (LEDs). It is to be appreciated that the light of other wavelengths may be used in conjunction with the concepts of this invention.

Brief Description of the Drawings

FIGURE 1 depicts a portion of a laser lightbar used in association with the present invention;

FIGURE 2 shows alignment of two components that allow laser light to pass through a second substrate, partially transparent at the wavelength of the light;

FIGURE 3 depicts a block diagram of an arrangement according to the present invention;

FIGURE 4 is a bottom view of FIGURE 3;

FIGURES 5a-5e illustrate process steps for the formation of a hybrid device according to the teachings of the present invention;

FIGURES 6a-6e are top views of FIGURES 5a-5e;

FIGURES 7a-7b shows selected process steps of a second embodiment according to the teachings of the present invention;

FIGURES 8a and 8b are top views of the process steps of FIGURES 7a-7b;

FIGURE 9 depicts a third embodiment in accordance with the teachings of the present invention;

FIGURE 10 is a block diagram of an arrangement implementing an LED printbar according to the teachings of the present invention;

FIGURE 11 is a bottom view of FIGURE 10;

FIGURE 12 depicts a block diagram of a further embodiment implementing an LED printbar according to the teachings of the present invention;

FIGURE 13 is a bottom view of FIGURE 12;

FIGURE 14 illustrates a block diagram of an imaging system designed for calibration of light signals implementing concepts of the present invention;

FIGURE 15 depicts timing of light and current readouts used in the calibration operation of the present invention; and

FIGURE 16 is a schematic of a driver element of the driver device of FIGURE 14.

Detailed Description of the Embodiments

The following description will primarily focus on a system employing a laser printbar. However, it is to be appreciated the present invention may also be used in conjunction with a LED array or other appropriate light emitting device or system, also for purposes other than printing. Further, the following discussion emphasizes

that the described configuration is sufficiently transparent to be used in sensing output from a printbar. It is to be appreciated however, the concepts of the present invention may be used in applications where it is appropriate to have a sensor which absorbs a higher percentage, and possibly all light emitted by a light emitting device or system.

~~Turning to~~ FIGURE 1, illustrated is a section of a laser printbar **10** having individual lasers **12** ~~interleaved~~ at a 3 μm pitch spacing.

Printbar **10** may be designed using gallium arsenide (GaAs), and lasers **12**, in one embodiment may be Vertical-Cavity Surface-Emitting Lasers (VCSELs). A laser emission cone **14** is shown for one laser to illustrate that the typical divergence of a VCSEL beam can be smaller than 20°.

FIGURE 2, is a cross-section of a spring contact device **16.** A first portion of spring contact device **16** is silicon or glass substrate **18** which has patterned thereon micro-spring interconnects (also called spring contacts) **20** and **22**. Device **16**, in one embodiment, further includes printbar **10**, having an array of lasers **12**, a first driver chip **24** and a second driver chip **26**. Each of driver chips **24** and **26** may control operation of the lines of one side of the array of lasers **12**. Spring contacts **20** and **22** are designed to provide an electrical connection between driver chips **24, 26** and printbar **10**. The electrical connection between chips **24, 26** and printbar **10** can be obtained by bonding these elements to spring contacts **20** and **22**. It is to be noted that although not shown, printbar **10** and chips **24, 26** may but do not need to be carried on a further-substrate. Driver chips **24, 26** receive image data which are converted into signals delivered to printbar **10**. The signal driver chips **24, 26** selectively control operation of lasers **12**, such as VCSEL-type lasers, which generate a light beam **28** in accordance with received image data, and emit the beam **28** through substrate **18**. Therefore, it is necessary that substrate **18** be partially transparent to light in the frequency range emitted by lasers **12**. In this embodiment, lasers **12** generate a wavelength shorter than 870 nanometers, in the infrared (IR) range.

One arrangement of a printbar and spring contacts is disclosed in U.S. Patent No. 5,944,537, to Smith et al., entitled, Photolithographically Patterned Spring Contact and Apparatus and Methods for Electrically Contacting Devices, issued August 31, 1999, hereby incorporated by reference.

A method of packaging devices being contacted with micro-springs is disclosed in Xerox Patent Application D/99734, to Chua et al., entitled Method and

Apparatus for Interconnecting Devices Using an Adhesive, filed December 15th,1999, commonly assigned and hereby incorporated by reference.

Spring contacts **20** and **22** are photolithographically patterned on substrate **18** and designed for electrical connections between devices. An inherent stress gradient in each spring contact causes free portions of the spring contacts to bend up and away from the substrate when a sacrificial layer is selectively removed. An anchor portion remains fixed to the substrate. The spring contact is made of an elastic material and the free portions provide for compliant contacts between devices for an electrical interconnection.

In one embodiment such contacts are designed in accordance with the teachings of U.S. Patent No. 5,613,861 to Smith et al., entitled, "Photolithographically Patterned Spring Contact"; U.S. Patent No. 5,848,685 to Smith et al., entitled, "Photolithographically Patterned Spring Contact"; U.S. Patent No. 5,914,218 to Smith et al., entitled, "Method for Forming a Spring Contact"; and U.S. Patent No. 5,944,537 to Smith et al., entitled, "Photolithographically Patterned Spring Contact and Apparatus and Methods for Electrically Contacting Devices", all commonly assigned and hereby incorporated by reference.

Implementing spring contacts **20, 22**, allows printbar **10** to be bilaterally electrically connected to driver chips **24, 26**. When printbar **10** and driver chips **24,26** are moved to contact under the construction of FIGURE 2, a gap of approximately 20μm gap separates the surfaces of elements **10, 24** and **26** from the surface of the spring contacts' substrate, element **18**. For a laser printbar and arrangement such as described in FIGURES 1 and 2, the issue of non-uniformity between the many different lasers **12** is a significant problem.

The present application describes devices and systems to correct the non-uniformity in light output, by provision of a system that uses a sensor that monitors the output of each light source to assist in calibration operations where the sensor is integrated on a substrate with spring contacts. The values resulting from the calibration are stored in an electronic look-up table, or by some other data storage method that can be referenced to normalize the output of individual light sources in-situ, by implementing periodic calibration operations.

FIGURE 3 illustrates an embodiment of the present invention shown as a hybrid structure **30** similar to what was depicted in FIGURE 2, however, in this

design a sensor **34** and spring contacts **20, 22** are integrated on the same substrate **32**. It is to be noted that substrate **32** as well as sensor **34** are partially transparent and laser beam (IR radiation) **28** is capable of passing substantially unobstructed through substrate **32**, and sensor **34**. By forming sensor **34** in a fashion which allows it to be aligned with a high degree of precision in front of lasers **12**, it is possible to obtain in-situ information as to laser output for each of lasers **12**, and provide periodic calibration of printbar **10** for an operational imaging device.

FIGURE 4 depicts a bottom view of FIGURE 3. Sensor **34** and spring contacts **20, 22** are on substantially the same plane nearest the page surface, and lasers **12** of printbar **10** for connection to spring contacts **20, 22** are at the back of the page. Contact pads **36**, shown in FIGURE 4, are pre-patterned on printbar **10** for connection with micro-springs **20, 22**. Sensor feedback lines **38, 39** are shown extending from sensor **34**. Sensor feedback lines **38, 39** carry readout current used in the calibration operation. FIGURE 4 emphasizes the importance of alignment between sensor **34** and the array of lasers **12**, and that sensor **34** is sufficiently sized to cover all lasers **12** in this embodiment.

FIGURES 5a-5e and 6a-6e are cross-sectional and top views of the process to form a device having contact springs **20, 22** and sensor **34** integrated on a single substrate **30**. In order to accomplish this integration, it is necessary for the sensor to be configured to have certain unique properties. In this embodiment, the first characteristic is that the sensor be made large enough to be aligned with all lasers **12** of printbar **10**. Presently a printbar having a laser array of approximately 4cm by 200μm is anticipated for use in an imaging device.

The second characteristic requires the sensor to be partially transparent to the laser light. As previously noted, this requirement allows for the operation of calibration without moving the printbar out of the printing area.

The third characteristic is for the sensor to have a high "contrast ratio", also called "light-to-dark" response. Since the sensor will only absorb a fraction of the light passing therethrough, due to its partially transparent nature, it must be able to work even with very small signals. An ideal sensor will have no current flowing when no light exists. Amorphous silicon (a-Si:H) sensors are able to approach this ideal state.

The fourth characteristic is that the manufacturing process for the sensor must be compatible with the manufacturing process of spring contacts.

Further, in this embodiment, the fabrication process depicted in FIGURES 5a-5e and 6a-6e, must ensure that when the integrated device is formed and contacted to a printbar, the sensor and spring contacts are properly aligned in relation to the lasers and the driver chips.

With particular reference to the process flow for the construction of a device formed on a substrate integrating both spring contacts and a sensor, in a first stage (stage 1), on a transparent silicon or glass substrate **40** is deposited or grown a transparent/conductive layer **42**, such as iridium tin oxide (ITO), which is patterned in accordance with known techniques. Transparent/conductive layer **42** needs to be transparent such that it does not block light emitted from lasers **12** (of FIGURES 3 and 4), and is required to be conductive as it will act as a first electrode of the sensor. FIGURE 6a depicts a top view of stage 1.

Turning to stage 2, illustrated by FIGURES 5b and 6b, a hydrogenated amorphous silicon sensor (a-Si:H) component or active layer **44** is grown on top of the first transparent/conductive layer **42**. a-Si:H sensor component **44** is usually comprised of three layers. The first layer **44a**, is a n^+-doped layer of material, typically less than 1,000 angstroms in thickness. Though not limited thereto, the first layer **44a** may be a n^+ phosphorous-doped amorphous silicon, or n^+ arsenic-doped silicon. A second layer **44b** is intrinsic amorphous silicon, of a thickness less than a micron, preferably in the range of 3,000-5,000 angstroms. The third layer **44c** of sensor element **44** is a p^+doped amorphous silicon of approximately 100 angstroms thickness. An example of a p^+-doped amorphous silicon which may be used as third layer **44c** is p^+ boron-doped amorphous silicon.

Following deposition of sensor element **44**, a second transparent/conductive layer **46** is deposited on top of sensor element **44**. Sensor element **44** and second transparent/conductive layer **46** may be patterned together in a single process or separately. Further, sensor element **44** in the present embodiment is an amorphous silicon sensor, which is opaque in visible light, and transparent at IR wavelengths.

Turning to step 3 of the process, shown in FIGURES 5c and 6c, passivation/release layer **48** is deposited. Passivation/release layer **48** is required to meet the manufacturing requirements of both the sensor configuration and spring contacts. One type of substance that meets this requirement of compatibility is

amorphous silicon-nitride. Oxynitride, and polyamide are among other possible choices. In particular, layer **48** acts as a passivation layer for the sensor by being electrically insulating and is transparent in the wavelength range emitted by the lasers which the sensor is to be associated. Layer **48** also functions as a release/sacrificial layer that may be used in the configuration of the spring contacts, as will be described in greater detail below.

Two vias are provided through passivation/release layer **48** to allow contact to transparent/conductive layers **42** and **46**. First via **50** and second via **52** may be seen clearly in top view FIGURE 6c. The first via **50** provides an opening to second transparent/conductive layer **46** and second via **52** provides an opening to first transparent/conductive layer **42**. These openings are necessary since the passivation/release layer **48** is formed from an electrically insulating material and, since layers **42** and **46** act as electrodes of the sensor, these openings provide access to layers **42, 46**.

At this point, an electrically protected sensor **53** is formed consisting of first transparent/conductive layer **42**, sensor element **44**, second transparent/conductive layer **46** and passivation/release layer **48**, and vias **50, 52** which provide electrical access to sensor **53.**

Attention is now directed to stage 4 of the process, as illustrated in FIGURES 5d and 6d. In this stage, metal patterns **54a-n, 56,** and **58** are deposited directly onto passivation/release layer **48** and into vias **50** and **52**. Metal patterns **54a-n**, **56**, and **58**, are deposited during the same processing steps and are made of the same metal layers, formed to have an inherent stress gradient.

In one preferred embodiment, metal patterns **54a-n**, **56**, and **58** are made of an extremely elastic material, such as a chrome-molybdenum alloy or a nickel-zirconium alloy. Depositing of the metal patterns **54a-n**, **56**, and **58** may be achieved by many methods including electron-beam deposition, thermal evaporation, chemical vapor deposition, sputter deposition or other methods.

The metal layers that compose patterns **54a-n**, **56** and **58** may be thought of as deposited in several sub-layers to a final thickness. A stress gradient is introduced into the metal layers by altering the stress inherent in each of the sub-layers. Different stress levels can be introduced into each sub-layer of the deposited metal during the deposition processing. After metal layers for patterns **54a-n, 56** and **58** have been deposited, they are patterned by photolithography into desired designs.

The process of depositing metal layers for patterns **54a-n, 56** and **58** in separate sub-layers results in the patterns **54a-n, 56** and **58** having a stress gradient which is compressive in a lower metal layer becoming increasingly tensile toward the top metal layer. Although the stress gradient urges the metal layers that compose patterns **54a-n, 56** and **58** to bend into an arc, patterns **54a-n, 56** and **58** adhere to the passivation/release layer **48** and thus lays flat.

In step 5, as depicted in FIGURES 5e and 6e, free portions **60a-n** of metal patterns **54a-n** are released from passivation/release layer **48** by a process of under-cut etching. Passivation/release layer **48** is typically deposited by plasma chemical vapor deposition (PECVD) and can give passivation/release layer **48** a fast etch rate characteristic. After proper photolithography a selective etchant, typically a HF-based solution, may be used to etch the passivation/release layer **48**. The etchant is called a selective etchant because it etches passivation/release layer **48** faster than the selective etchant removes metal from metal patterns **54a-n**. By means of the etch process free portions **60a-n** are released from passivation/release layer **48** and allowed to bend up and away from substrate **40** due to the stress gradient in metal layers **54a-n**.

Another wet etchant which may be used is a buffered oxide etchant (BOE) which is hydrofluoric acid combined with ammonium fluoride. Also proper choice of the passivation/release material can allow a dry-etching technique for the release process.

Metal patterns **56, 58** comprised of the same stressed metal design of patterns **54a-n**, are not released, and are used as sensor readout lines and contact elements to the first transparent/conductive layer **42** and second transparent/conductive layer **46**, which act as electrodes for sensor **53**.

FIGURES 5e and 6e depict a sensor/contact semiconductor integrated device **62** which carries sensor **53**, an amorphous silicon active device, together with stressed spring contacts **54a-n** designed to contact devices on a separate substrate.

It is again worth noting that substrate **40**, first transparent/conductive layer **42**, second transparent/conductive layer **46**, and passivation/release layer **48** are each transparent at the frequency of operation of VCSEL lasers **12** of printbar **10**. Sensor element **44** is partially transparent.

Interference is a phenomenon that can alter the reflection from a surface. It can be designed beneficially to obtain anti-reflection characteristics, reducing reflection losses.

Light being directed to sensor **53** may either be absorbed, passed through, or reflected. Reflection of light is undesirable as compared to the other possibilities, since if light is absorbed, the sensor is using it to determine an appropriate feedback to the system, and if light passes through, it is being used by the target device, for instance to create a latent image on an electrostatic drum or for other useful purposes. On the other hand, reflected light is wasted light.

The interference phenomenon is dependent upon the thickness of layers comprising sensor **53** and the wavelength used by laser **12**. Sensor **53** has been designed in consideration of the interference phenomenon, and the thickness of the layers have been adjusted to avoid or minimize undesirable reflection for the light frequency of lasers **12**. In particular, passivation/release layer **48** has a thickness of 3,000 angstroms to obtain the desired non-reflective effect.

Turning to FIGURES 7a-b and 8a-b, a second embodiment of the present invention is illustrated. It is known that prior to a laser starting its lasing process a phenomenon takes place known as spontaneous emissions. During the spontaneous emissions, light in the visible range from the laser may be emitted. It is undesirable to have this light, as well as light of any other undesired wavelength, reaching sensor element **44**. Therefore, to further improve the reliability of the present invention, when IR lasers are used, an additional processing step may be added. Particularly, after the application of second transparent/conductive layer **46** (as depicted in FIGURE 5b), a visible light absorption layer **64**, which may be hydrogenated amorphous silicon (a-Si:H), is deposited on top of second transparent/conductive layer **46** prior to sensor element **44** and second transparent/conductive layer **46** being patterned. Visible light absorption layer **64** is opaque to visible light, and transparent to IR light. Once sensor element **44**, second transparent/conductive layer **46** and visible light absorption layer **64** have been deposited on top of first transparent/conductive layer **42**, they are patterned. Next, and similar to FIGURE 5c, passivation/release layer **48** is deposited over this patterned stack, and over transparent/conductive layer **42** and substrate **40**. Thereafter, and as shown in FIGURES 7a and 8a, vias **65** and **66** are provided through passivation/release layer **48** and visible light absorption layer **64**, to provide access to transparent/conductive layers **46** and **42**. By this design, an electrically isolated sensor **67** is formed.

As depicted in FIGURES 7b and 8b, stressed metal layers for patterns **54a-n** and **56** and **58** are deposited in a manner similar to that discussed in relationship to

FIGURES 5d and 6d. Thereafter, selected portions of patterns 54**a-n** are released by the etching process previously discussed, to form integrated device **68**.

The embodiment shown in FIGURES 7a-7b and 8a-8b adds visible light absorption layer **64**, which provides a manner of inhibiting spontaneous emissions generated visible light from impinging upon sensor element **44**. This avoids false readings from sensor **67**, which would negatively impact the calibration process.

When the laser goes above the laser threshold, spontaneous emissions may still exist, too. An ideal sensor would be "blind" to the spontaneous emission component, i.e. it would have a very narrow bandwidth. Therefore it would read nothing but the lasing component of the laser operation. Absorption layer **64** is able to absorb the continuing spontaneous emissions, so that it does not reach sensor element **44**.

In one embodiment, absorption layer **64** is a-Si:H of 1 micron thickness, or preferably approximately 3,000-5,000 angstroms, thick. Other materials having the capability of absorbing undesired light and allowing the desired wavelength to pass may also be used. It is noted that amorphous silicon will change in sensitivity dependent upon the wavelength of light. By absorbing the visible light, a more accurate reading is obtained. In a further embodiment, visible light-absorbing layer **64** may be constructed directly on the output of lasers **12.**

Turning to FIGURE 9, the cross section of an integrated device **70** is illustrated having a transistor, e.g. Thin-Film Transistor (TFT) switch **72** configured below a semi-continuous sensor **74**, which is integrated with contact springs **76a-n**, similar to spring contacts **54a-n** of FIGURES 5e and 6e. In this embodiment, p-i-n-amorphous silicon (a-Si:H) sensor **53** of FIGURES 5e and 6e is replaced by a more elaborate composition. The combination of TFT switch **72** and semi-continuous sensor **74** are meant to be shown as a pixel, or picture element of a 1- or 2-dimensional array, enclosed in a layer of passivation, for operation as an active matrix sensor.

With more particular attention to the construction of device **70**, deposited on a transparent substrate **80** such as glass, is a gate contact **82** formed of a transparent metal, such as Chronium (Cr). Metal layer **82** is deposited in a thickness of approximately 3,000 angstroms, and acts as the gate contact of TFT switch **72**. Deposited over metal portion **82**, and remaining portions of substrate **80**, is a first transparent/conductive layer **84**, such as nitride, oxynitride, polyamide or other

appropriate material, which is typically deposited to approximately 3,000 angstroms in thickness. Deposited over layer **84** is a layer **86** of an intrinsic hydrogenated amorphous silicon (a-Si:H), typically 500 angstroms thick.

An island of nitride (oxynitride, polyamide, etc.) **88** is deposited and patterned over gate contact **82** on the a-Si:H layer **86**. Island **88** is typically deposited to a thickness of approximately 2,000 angstroms.

A layer of n-doped a-Si:H **90** is then deposited and selectively patterned to a thickness of approximately 1,000 angstroms over nitride island **88** and layer **86**.

Next, a layer of transparent conductor **92** is deposited on top of island **88**, and an opening **94** is patterned to create two electrodes **92a, 92b** from layer **92**. The metal of layer **92** may typically be a Indium Tin Oxide (ITO) . Patterns **92a** and **92b** act as the source and drain contacts for TFT transistor **72**. A passivation layer **96** is patterned on top of conductor layer **92** and may typically by oxynitride of approximately 1 micron, or alternatively a polyamide layer of approximately 2.3 microns thickness. A via in layer **96** is opened, such that a transparent/conductive layer **98**, typically made of ITO, and an n^+-doped amorphous silicon layer **100,** are deposited and patterned in a mushroom-shape inside and over the via. Layer **98** functions as the bottom electrode of sensor **74.** Layer **98** is deposited such that, in the via, it is in contact with layer **92** and over remaining portions of layer **96**. The n^+-doped contact layer **100** is typically 700 angstroms thick..

A continuous layer of intrinsic amorphous silicon (a-Si:H) **102** is deposited over the n^+-doped contact **98** and portions of the passivation layer **96**. This layer of sensor **74** has a typical thickness of approximately 1 micron.

A p^+-doped layer **104** is then deposited over intrinsic a-Si layer **102** to a thickness of approximately 100 angstroms. A transparent/conductive layer **106**, typically made of ITO and 5,500 angstroms thick, acts as a top electrode of sensor **74**. Thereafter, a top passivation/release layer **108** is deposited and patterned in accordance with the description of FIGURES 5d-5e and 6d-6e, and metal layers are deposited in accordance with the previous embodiments.

This embodiment of integrated detector/contact spring device **70**, therefore, consists of a TFT transistor **72** which is connected to the semi-continuous sensor **74** through the opening created in passivation layer **96**. The sensor **74** is otherwise separated from the TFT on a top level by portions of passivation layer **96** that have not been etched away.

After formation of an integrated detector/contact spring device, such as devices **62**, **68** or **70**, alignment is made with a substrate carrying printbar **10** or the light source of interest. It is then desirable to determine the performance of a system configured by electrically contacting printbar **10** with driver chips **24, 26** (FIGURE 3) through use of integrated sensor/contact spring devices **62**, **68** or **70**. Therefore testing was undertaken to determine the operating capability of sensor **53** in a system as described.

Initially, a given power was applied to a single laser **12**, and the output signal generated by sensor **53** was monitored as a result of the input power. Typically, for 1 milliwatt of light output, the signal of the photo-current provided by sensor **53** was approximately 1 micro-amp of photo-current. The dark current, the current that is produced when no light exists, was 1 pico-amp or less.

For the sensor size suggested in the case of the 1,200dpi- the contrast ratio between the sensor current under laser illumination and in the dark is therefore about 1,000,000, allowing in principle for 10-bit resolution. In this embodiment, a 4-bit correction has been used and can already provide substantial quality improvement to the system.

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Turning to the calibration process, it is noted that in a first embodiment, calibration of lasers **12** of printbar **10** is accomplished by sensing and calibrating a single laser at a time. Particularly, sensors (**34, 34', 53, 68, 74**) are sufficiently sized to be placed in front of all lasers **12** of printbar **10**. In one calibration scheme, the imaging device is not being used to print an image during calibration. Rather, the calibration process takes place during a time when image processing is not occurring.

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In the embodiment describing the laser printbar, it is assumed sensors **53, 68, 70** are rectangular sensors of approximately 4cm by 200 micrometers, which is large enough to intercept 100% of the laser beams diverging from printbar **10**, for a substantially 4cm-long laser array. The typical divergence of the VCSEL's beam was noted to be smaller than 20°.

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The transparency of the amorphous silicon film ensures sufficient laser radiation to exit from the sensor to allow for printing while low (10pA/cm^2) dark leakage current of sensors **53, 68, 70** maintains the contrast ratio (or light-to-dark ratio) at a high enough value for operation.

Turning attention to FIGURES 10 and 11, a configuration similar to that shown in FIGURES 3 and 4 is depicted, and the same elements are provided with the same numbers. In this embodiment, the printbar is an LED printbar **10'**. It is noted that light from an LED is non-coherent unlike the light from a laser and it is typically much more diverging. This is illustrated by light beam **28'** of FIGURE 10. While an LED lightbar may be incorporated into a configuration such as shown in FIGURES 3 and 4, the particular characteristics of LED light are more fully taken advantage of in the present embodiment.

Sensor **34'**, as shown more particularly in the bottom view of FIGURE 11, is manufactured having an elongated open "o"-shaped configuration, one end of which is shown in the figure. It runs along the full length of the LED printbar, with two leg portions **34a'** and **34b'**, whereby an opening **34c'** is provided over the LEDs **12'** of LED printbar **10'**. Such a design recognizes the diverging characteristics of an LED light source, and positions sensor **34'** such that sensing elements **34a', 34b'** are at the edges of the LED light beam **28'**. By this design, the direct LED light path, which is emitted through the open section **34c'**, is undisturbed and therefore substantially 100% of this light source may pass to the intended target. Sensor **34'**, is able to detect the value of the light being emitted by sensing the light in the shoulder or edge portions of light beam **28'**.

It is to be noted that using such a design, all of the light from the shoulder portions of beam **28'** may be absorbed and sufficient LED light may still be emitted through opening **34c'** to allow sufficient light emission for the intended target. Depending on the system it will be embedded in, this can allow sensor configurations where the transparency to the light is almost zero. In situations where the entire portion of the shoulder beams of light **28'** is not absorbed, due to the incoherent nature of the LED light, that portion of the light passing through sensor **34'** will join the central portion of beam **28'** which has not been disturbed by sensor **34'**.

The foregoing design is particularly useful in connection with LED printbars since they have a less powerful light beam than a laser light beam. Thus, by not absorbing the center part of the light emission, a more efficient imaging system is provided.

Turning to FIGURES 12 and 13, an embodiment similar to that shown in FIGURES 10 and 11 is provided. However, in these figures, in addition to sensor **34'** being provided with an opening, i.e. the elongated open "o"-shaped configuration, a

similar concept is implemented with the substrate **32'**. This design is particularly illustrated in FIGURE 13 where it is shown that substrate **32'** is provided with a glass opening **32a'**. It is noted that while FIGURE 12 appears to have substrate **32'** as two separate elements, in actuality and as illustrated more completely in FIGURE 13 there is simply an intermediate rectangular section of glass substrate **32'** which has been removed by any suitable etching technique, such as wet etching. FIGURE 12 describes a section across the integrated device.

Turning attention to FIGURE 14, a block diagram of a calibration/printing system **110**, according to the present invention is depicted. Driver chip **24** (which could also be driver chip **26**) is shown in association with printbar **10** and sensor **34**, (sensors **34', 53, 68, 70** or other appropriately formed sensor may also be used).

The only data link between printbar **10** and sensor **30**, through which information is passed, is the light transfer. Sensor **34** generates a readout current $\mathbf{I_s}$ which is carried on feedback circuit lines **38, 39.** This sensor readout current $\mathbf{I_s}$ is delivered to a comparator **112**, and compared to an external reference current $\mathbf{I_R}$. The value of external reference $\mathbf{I_R}$ is a parameter of the system set by a user or during system design. Comparator **112** measures the difference between readout current $\mathbf{I_s}$ and reference current $\mathbf{I_R}$ to obtain an offset current $\mathbf{I_{OFFSET}}$, which is delivered to current/voltage converter **114**, and this voltage is in turn provided to analog-to-digital (A-/D) converter **116.** In this embodiment A-/D converter **114** is shown as a four-bit A-/D converter. These four bits are routed to a set of low frequency shift-registers being used as an electronic look-up table **118,** which in this embodiment is comprised of four shift registers **118a-d**. Each bit of data enters the shift registers and ripples through as shown by arrow **120**.

In one embodiment, for a printbar having approximately 14,000 lasers, each shift register **118a-d** may be a 14k-bit shift having a serial input and a serial output. . The outputs of shift registers **118a-d** are supplied, in parallel, as a 4-bit word, to driver **122.** In the example in FIGURE 14, the output lines from the top stage of shift registers **118a-d** are delivered to the driver at a stage 1 position **124**, via input lines **125a-d**.

In an embodiment with 14,000 lasers, there will be approximately 14,000 stages each associated with a specific laser of printbar **10**. Therefore, each stage is connected or associated with a specific laser. For each stage, e.g. stage **124**, four bits from (MSB to LSB) are provided by shift registers **118a-d**. Each 4-bit value in each

stage acts as the correction value for that particular laser. It is to be appreciated that while four bits are described in this embodiment, systems with a larger or smaller bit number may also be implemented.

In the above-described section, the steps from sensing data representative of laser output, until a correction value is loaded into one of the stages of driver **122**, are accomplished at a comparatively slow rate. For example, a calibration operation as described for all lasers in a 14,000 array may take approximately 1-2 seconds.

In the case of a printbar, since calibration can be programmed to take place upon either start-up of the machine, during a rest period, or at predetermined times when the machine is not operating, the time to acquire and store the information into 4-bit driver **122** is not critical. Through this process 4-bit driver **122** has its inputs set to the correction values for each laser of printbar **10.** It is to be appreciated, however, that while this embodiment uses a separate time sensor readout and correction of the driver's inputs, with sufficiently timed actions and appropriate data handling, high-speed real-time, or near real-time calibration may be accomplished with a similar approach.

High-speed printers run data streams at a frequency much greater than that just described for this embodiment. Even if the calibration operation is not designed to keep up with the speed of the high-frequency data stream, by the process now described, this differential in speed is not critical as the correction values stored in the stages such as stage **124,** are already set at the inputs of the driver **122** when the high frequency data stream from shift register **126** is enabled. The values are set to stage **124**, via input lines **125a-d** from low frequency shift register **118**.

Turning now to a printing process using a printbar with approximately 14,000 lasers, data will be supplied via a high-frequency bit stream **127,** which may be provided through a print processor of a computer or other digital device. The high frequency data is supplied to a high frequency 14k-bit shift register **126** with a parallel output to form enable/disable outputs **126a-n** . The correction information stored at the inputs of stage **124** is used to adjust, with respect to a predetermined mean value, an activation signal **130a-n** supplied to printbar **10**, in order to generate an appropriate level of output for the corresponding laser. The outputs **126a-n** of high frequency shift register **126** are used to enable/disable the corrected current, for each stage, from being delivered from the driver to the corresponding laser. It is noted that in this

embodiment **126a-n** represents approximately 14,000 outputs and **130a-n** represents approximately 14,000 signals.

The correction value set at the inputs of the stages, such as stage **124**, therefore are stable values, held in the electronic look-up table **118.**

Returning attention to the calibration procedure, lasers **12** are, in this scenario, activated in a sequential one-at-a-time fashion and sensor **34** reads out the photo-current produced by each laser one at a time. The time response of the photodiode to the radiation pulse is virtually immediate and is limited by the readout electronics. The photo-current turn-off is related to the transient time of holes (slower photo-carriers) through the depleted intrinsic region. As illustrated in FIGURE 15, amorphous silicon transport properties very safely allow readout times of about 10μs, **132.** A 100μs idle time, **134** for a VCSEL type laser combined with an amorphous silicon p^+-i-n^+ photo-diode is considered desirable for clean operation. Given a sensor capacitance of 0.8nF (as calculated from a 10nF/cm^2 typical capacitance), the resistance of a read-out circuit can be as large as 1KOhms to widely maintain the 10μs readout constraint. In reality, the current is flowing into a virtual ground and resistance can therefore be made small.

The use of a single sensor for all the VCSEL lasers allow for an ease of fabrication and correct normalization of the power outputs even if the dark sensor leakage current would tend to degrade as the sensor ages. One reason why the sensor may degrade is illumination-induced defect creation (known as Staebler-Wronski effect). Defect creation will also alter the photo-response of the sensor. Since the same amount of radiation output (in a duty cycle) is expected on average for all the lasers during printing, this effect should not affect the system's performance. The use of a continuous sensor layer increases interaction between areas illuminated by adjacent VCSEL lasers and averages the previously discussed effect.

To prevent Staebler-Wronski effect from disturbing a correct calibration operation also, the sensor can be pre-degraded before use by exposure to light for an appropriately long time. Typically Staebler-Wronski effect degrades the sensor photo-response to about 70% of its initial value. Thereafter, the effect does not cause any further degradation and the performance of the sensor is to be considered permanently stable. The small reduction in the response to illumination is completely irrelevant given the extremely large on-to-off ratio previously noted. The thickness of a

amorphous silicon (a-Si:H) sensor is to be uniform to 2-3% on the area of interest. The effect in the uniformity on the intensity of the transmitted radiation is therefore small. Further, it constitutes a pattern at low spatial frequency, not particularly relevant for the human eye.

For a 14,000 VCSEL array, the total calibration time is approximately 1.54s, (i.e. 14,000 X 110μs) on the basis of a design according to the first embodiment of a single sensor.

To evaluate the effect of this time on throughput, these statistics are considered with a 600-page/minute printer. For such a printer, a page time of 100ms exists. Therefore, re-calibrating every 1000 pages (i.e. slightly less than once a minute) on such a high-speed printer would reduce the pages per minute output to 591 which is a 1.5% reduction in system output. The calibration per-1000-pages is not considered a requirement to detect laser aging and other problems. Therefore, considerably slower calibrations may be safely adopted and throughput will not be significantly affected even at these very high-speed printers.

The actual control of printbar **10** during printing operation is a more critical step due to a higher speed of signals in high-speed printing (e.g. 673 Mhz when two drivers are employed). An embodiment of a driver element **140** of driver **122** for one laser **12**, which may be used for this purpose, is shown in FIGURE 16. Driver **140** is based on CMOS electronics and has been designed for 4-bit uniformity correction. Such a device consists of a set of appropriate current mirrors, properly gated, and of the actual VCSEL driver stage. Each current mirror is comprised of a set of transistors **142a-e**, and a set of reference transistors **143** which are shared by all sets **142a-e**. Each current mirror **142a-d** is programmable by means of a set of the gating input lines **125a-d** Gate input lines **125a-d** are driven by the outputs of low frequency shift registers **118a-d**. The chosen current correction adds to the reference current delivered by the current mirror **142e**. The total output current to the light source (laser, LED or other similar one) is delivered by activation signal **130** by the output stage of the driver **122**. Output is enabled by enable signal line **126a**, of enable signal lines **126a-n** of FIGURE 14, when appropriate. High-frequency data are fed into high-speed shift register **128** and enabled out in parallel to print an entire line of an image. With continued attention to FIGURE 16, activation signal **130** corresponds to activation signal **130** of FIGURE 10.

In a further embodiment of the invention described above, background correction to suppress the small effect of the sensors' leakage current may be provided. This can be relevant when a many-bit correction is desired, such as 8 or 10-bit correction.

Another improvement can be realized by choosing an appropriate firing order for the VCSELs (or any other similar light source) during calibration, as opposed to a linear scan from one end to the opposite one. This assists in reducing the effect of local trapped charge in the intrinsic layer, relatively slow to be released and that might distort the local electric field and alter the photo-current. For example, this may be accomplished by firing alternatively opposite ends of the printbar. An appropriate storage path into the look-up table must be adopted accordingly.

The calibration process described is closed-loop but allows for only one cycle correction. In order to further optimize the system, more feedback cycles for each VCSEL may be added. This can be done either by repeating the process more than once and eventually adjusting the look-up table content further, or extending the duration of the VCSEL test pulse to more than one sensor readout time to obtain the same goal. The latter option (faster) requires changing the set of four shift registers to a slightly more elaborate system of individually addressable latches to repeatedly adjust the content of any cell among the 14k. Both solutions would slow the calibration process, although still in an acceptable way in order to keep a high throughput in printing.

An alternative to the uniformity correction obtained by drive current adjustment relies on the typical low duty cycle of the VCSEL pulse. A proper modulation of the duty cycle, as dictated by the look-up table values, will in fact provide a time-domain uniformity correction without altering the laser drive current.

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In a further embodiment, sensors **34, 34', 53, 68, 70** may be constructed as a plurality of sensors, into a sensor array. In this manner, instead of testing a single laser at a time, multiple lasers of multiple arrays may be tested in parallel. A drawback of using smaller sized arrays as opposed to a single sensor is that the sensor medium may age at different rates for different arrays used. An advantage is that the speed of the calibration process is increased by parallel operation and makes easier to push the calibration procedure toward real-time.

It is to be appreciated that the many aspects of the discussion concerning driving a VCSELs printbar also apply to LED printbars and to single light sources or

arrays of light sources that can be contacted by micro-springs and monitored by a proper sensor configuration integrated with the micro-springs.

A micro-spring interconnect structure consists of micro-springs used to electrically connect two or more devices. Such a structure can be used in embodiments where the springs are anchored on any of the devices being contacted. Therefore it is also to be appreciated that the micro-springs, for example in FIGURE 3, can be fabricated on the GaAs chip **10** instead of on the glass substrate **32**.

The foregoing is considered as illustrative only of the principles of the invention. Further, since numerous modifications and changes will readily occur to those skilled in the art, it is not desired to limit the invention to the exact construction and operation as shown and described, and accordingly, all suitable modifications and equivalents may be resorted to falling within the scope of the invention.